EORGIA INSTITUTE OF TECHNOLOGY

OFFICE OF CONTRACT ADMINISTRATION

PROJECT ADMINISTRATION DATA SHEET

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[ ] REVISION NO. ____

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DATE: 4/29/81

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itle: Modelling of an Optical Cavity for a 4-95 Stirling Engine Solar Receiver

DMINISTRATIVE DATA

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eports: See Deliverable Schedule

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ESTRICTIONS

ee Attached N/A Supplemental Information Sheet for Additional Requirements

ravel: Foreign travel must have prior approval - Contact OCA in each case. Domestic travel requires sponsor approval where total will exceed greater of $500 or 125% of approved proposal budget category.

quipment: Title vests with N/A; None authorized/proposed.

OMMENTS:

OPIES TO:

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EES Research Public Relations
Project File (OCA)
Other:

A-2881

INTERIM REPORT

DESIGN, FABRICATION, AND TEST OF A SOLAR THERMAL STIRLING ENGINE HEATER SYSTEM

PHASE I: DESIGN AND SPECIFICATION OF A SOLAR THERMAL RECEIVER FOR THE UNITED STIRLING 4-95 ENGINE

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P.E. Mackie

Project Number A-2881-000

July 1981

Prepared for

United Stirling
Malmo, Sweden

Energy and Materials Sciences Laboratory
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INTRODUCTION

The objective of this phase of the program was to design a cavity solar receiver which could be built around a standard, or almost standard, United Stirling 4-95 engine heater assembly. Several inexpensive materials were investigated to determine suitability for providing a diffuse-reflective coating for the inside cavity walls.

A number of cavity configurations were analyzed optically to determine optimum cavity geometry and to determine the flux absorbed by the heater tubes. Thermal analyses were carried out on some of these configurations.

OPTICAL ANALYSIS

Georgia Tech's optical analysis program traces a bundle of rays, consisting of a central ray from the solar disc and 12 additional rays,from a point on the concentrator surface to a point on the receiver surface. Each ray is weighted according to its point of origin on the sun and according to its location on the concentrator. The process is repeated for many points (typically 600) along a "line" on the concentrator and axial symmetry of the flux pattern on the receiver surface is assumed. Each bundle of rays is given a random error, with the totality of errors having a normal distribution, to model the slope error of the concentrator.

The first cavity configuration on which an optical analysis was performed is shown in Figure 1. This is the same configuration which was analyzed for United Stirling in an earlier program, but some improvements had been made to the optical analysis program in the intervening months and it was considered advisable to reestablish the baseline design. All cavity models assume a diffuse reflectivity of 0.1 for the heater surface and 0.9 for all other cavity surfaces. The optical efficiency of this configuration, using the flux pattern from the Advanco concentrator, is 72.3 percent. Optical efficiency is defined as flux absorbed by heater tubes/flux incident on aperture plane. The heater tube involute was modeled as being solid for this analysis.

The second configuration is shown in Figure 2. The "trap" near the base of the heater assembly has been eliminated. Optical efficiency, under the same conditions, is 74.8 percent. Figure 3 shows a larger diameter cavity, wherein the optical efficiency is again only 72.3 percent, so it appears that reducing cavity diameter is a step in the right direction. In the next configuration, the cavity diameter was reduced to 340 mm, as shown in Figure 4. The optical efficiency was increased to 75.7 percent. Next, we moved the heater assembly 3 cm closer to the focal plane (Figure 5). This increased the optical efficiency to 84 percent. Moving the heater assembly still closer to the focal plane by 2 cm (Figure 6) increased optical efficiency to 85.5 percent. Since this last configuration change produced only a modest efficiency improvement, and since the incident flux on the center plug increased to 11.3 KW, we concluded that the cavity diameter and heater location shown in Figure 6 is very nearly optimum.

In the first six configurations studied, the aperture diameter was 19 cm. We next analyzed the configuration of Figure 6 with an 18 cm diameter aperture. Aperture plate interception increased from 0.3 to 0.5 KW and optical efficiency dropped to 85.2 percent. Next, the Figure 6 configuration was analyzed using the ACTF flux pattern with a 19 cm aperture. Optical efficiency was 83.4 percent. See Figure 7. Figure 7 has a transparency factor built into the heater, so it is not directly comparable.

The extended heater configuration shown in Figures 8-12 was analyzed, using the Advanco flux pattern. The optimum configuration was analyzed using the ACTF flux pattern (Figure 13). The Advanco flux pattern resulted in an optical efficiency of 92.5 percent for optimized heater depth, while the ACTF flux pattern produced an optical efficiency of 94.4 percent.

At the request of United Stirling, an additional analysis was carried out. This analysis was conducted for the same configuration as Figure 6, except that the heater tip to focal plane distance was increased to 262 mm. This change reduced optical efficiency to 73.6 percent. See Figure 14.

THERMAL ANALYSIS

Although it was not anticipated originally that thermal analysis could be performed within the time period allotted for this program, it soon became apparent that attempting to design a receiver without some idea of temperatures which would be encountered would leave too many uncertainties. Therefore, we set up a thermal analysis model to be analyzed using MITAS II. Since a MITAS model is rather time-consuming to set up (although, once the geometric model is established, it is relatively easy to study the effects of varying non-geometric parameters) only two configurations were analyzed - that represented by Figure 6 and the deep cavity configuration (262 mm from aperture plane to heater tip). The optical analysis program was modified to allow some rays to pass through the involute section of the heater assembly, thus improving the accuracy of the incident flux data.

The MITAS model consisted of a section of the receiver from the centerline of a heater tube to the centerline of the adjacent heater tube (1/72 of the circumference); 28 nodes were used. Radiation losses and heat transfer to the helium were modeled accurately. Conduction and convection losses were lumped together, with an assumed h of 2.0 Btu/ft^2-hr-^{o}F since details of the structure affecting conduction losses were not well known.

Cavity temperatures are shown in Figures 15-19. Overall efficiency (flux into helium/flux at focal plane) values are given in Table I, as well as heat flux into the helium. Figure 20 shows the flux pattern used to generate Figures 15 and 16. Figure 17 corresponds to the flux pattern in Figure 7, while Figures 18 and 19 correspond to the flux pattern in Figure 14.

TABLE I

	Shallow Advanco		Cavity ACTF		Deep Cavity (Advanco Flux Only)	
	1200^o Helium	1500^o Helium	1200^o Helium	1500^o Helium	1200^o Helium	1500^o Helium
Heat into Helium (KW)	53.8	52.4	27.6	(Not	50.14	49.2
Overall efficiency	79.5%	77.5%	81.3%	Run[1])	74.2%	70.9%

MATERIAL TESTING

A simple experiment was devised to test several materials which appeared suitable as diffuse reflective coatings for cavity walls. We began with 4 wedge-shaped 1/8-inch thick cold rolled steel sheets. One was painted with high temperature paint, rated at 1200^o F. The second was plasma-sprayed with alumina. The third was plasma-sprayed with magnesium zirconate, while the fourth was covered with a section of a fire brick.

Other than keeping the experiment simple, the rationale for doing a flat plate experiment, as opposed to a cavity experiment was that the higher

[1]There is insufficient flux within 19 cm in the present ACTF pattern to achieve this temperature.

radiation and convection losses from the flat plate might approximate the heat sink effect of the heater tubes. The rationale for choosing magnesium zirconate was that magnesia (which we thought would be superior to alumina) is impossible to plasma spray, so we compromised with magnesium zirconate. Before the test, the samples were covered with a Kao-wool blanket which withstood the solar flux very well, so the experiment actually tested Kao-wool also.

We had planned to locate the samples well above the focal plane in a flux of 10-20 watts/cm^2 and move down until the samples failed. The flux at the plane where the samples were located was approximately 40 watts/cm however, and the paint and the magnesium zirconate failed almost immediately. The alumina survived the first run and seemed to be surviving a number of partial heating and cooling cycles. It ultimately peeled off after completely cooling.

The conclusion was that none of the materials tested except Kao-wool would be suitable for a cavity liner. A material tested previously, WRP-SA-AQ-Felt (Refractory Products Co.) would also be satisfactory. There are several improvements which could be made on the plasma sprayed alumina. It was not sufficiently dense to protect the steel from rusting, and the sample had darkened noticeably at the time the test was conducted. This could have been prevented by nickel plating the steel before plasma-spraying. The nickel may have helped additionally by providing a pliable medium to cushion the differential thermal expansion between the steel and the alumina. This potential improvement could not be investigated within the time and financial framework of this program, however.

CONCLUSION

The simple cavity structures analyzed will serve as fairly good solar receivers, reaching overall efficiency of nearly 80 percent. The extended heater tube configuration looks very good optically and should be capable of even higher overall efficiency. The diffuse-reflective cavity walls run somewhat hotter than we had expected at the beginning of the program, but this should not pose a serious materials problem.

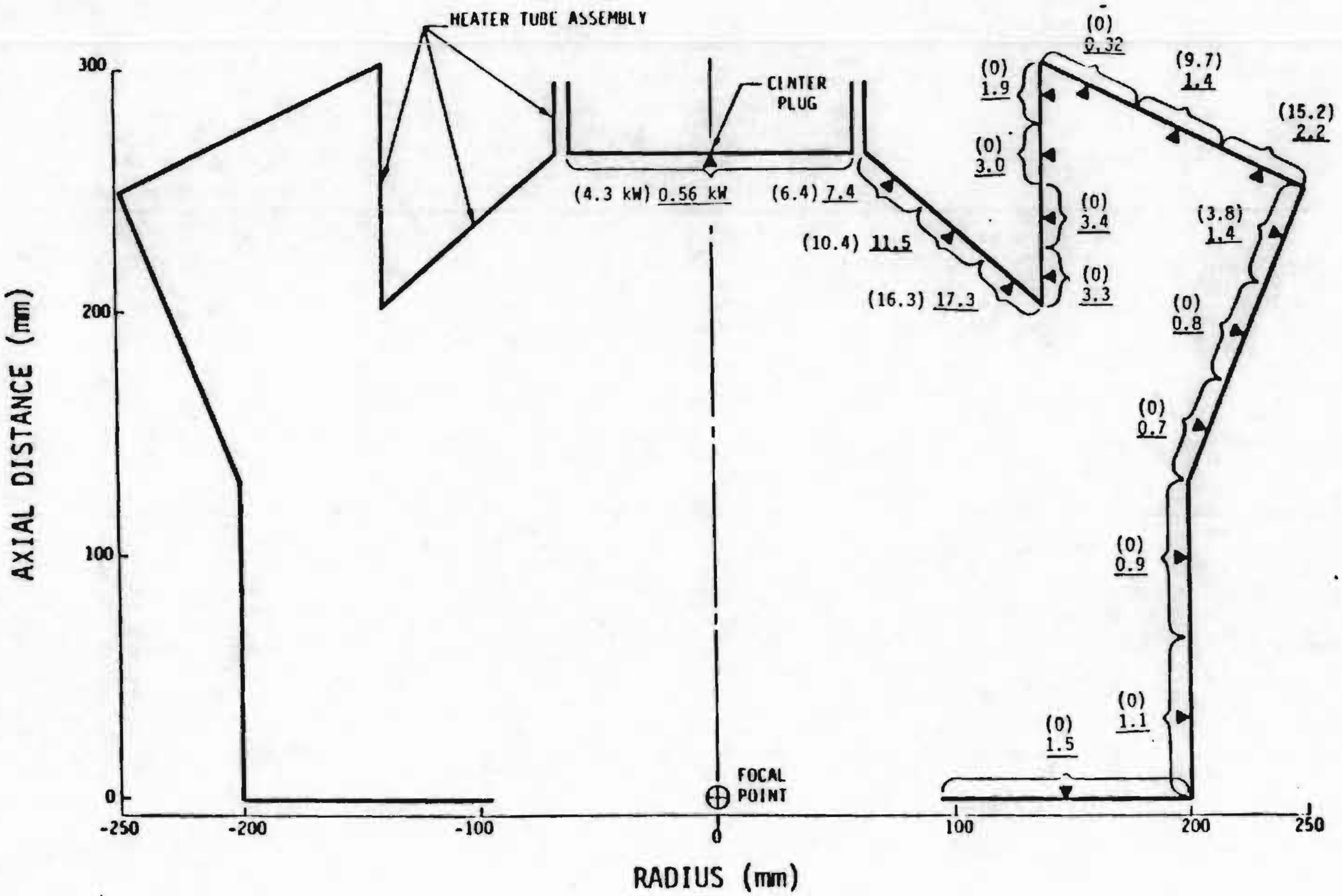

Figure 1. Cavity Configuration #1. Advanco Flux Pattern
(X.XX) Incident Flux. X.XX Net Flux.

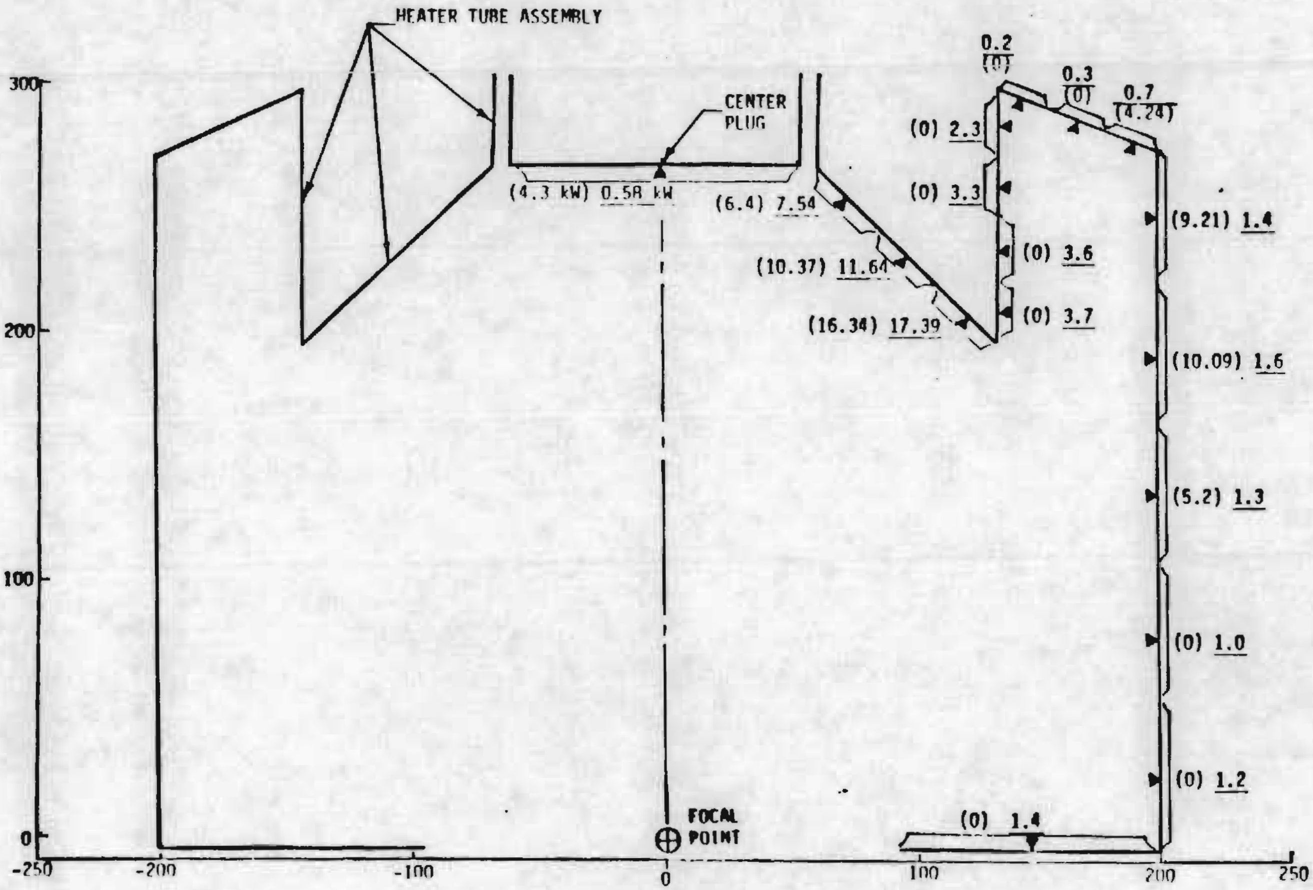

Figure 2. Cavity Configuration #2. Advanco Flux Pattern
(X.XX) Incident Flux. X.XX Net Flux.

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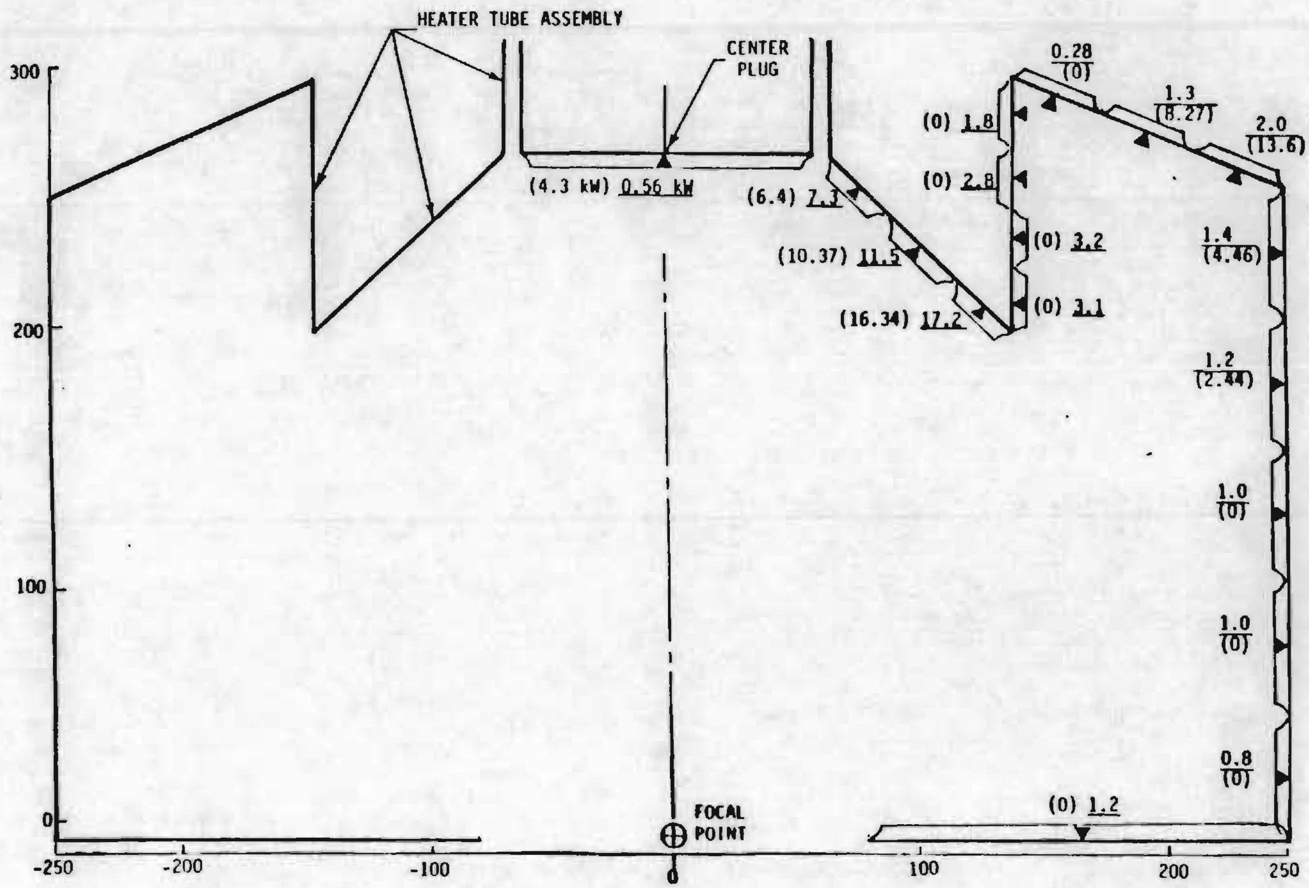

Figure 3. Cavity Configuration #3. Advanco Flux Pattern (X.XX) Incident Flux. X.XX Net Flux.

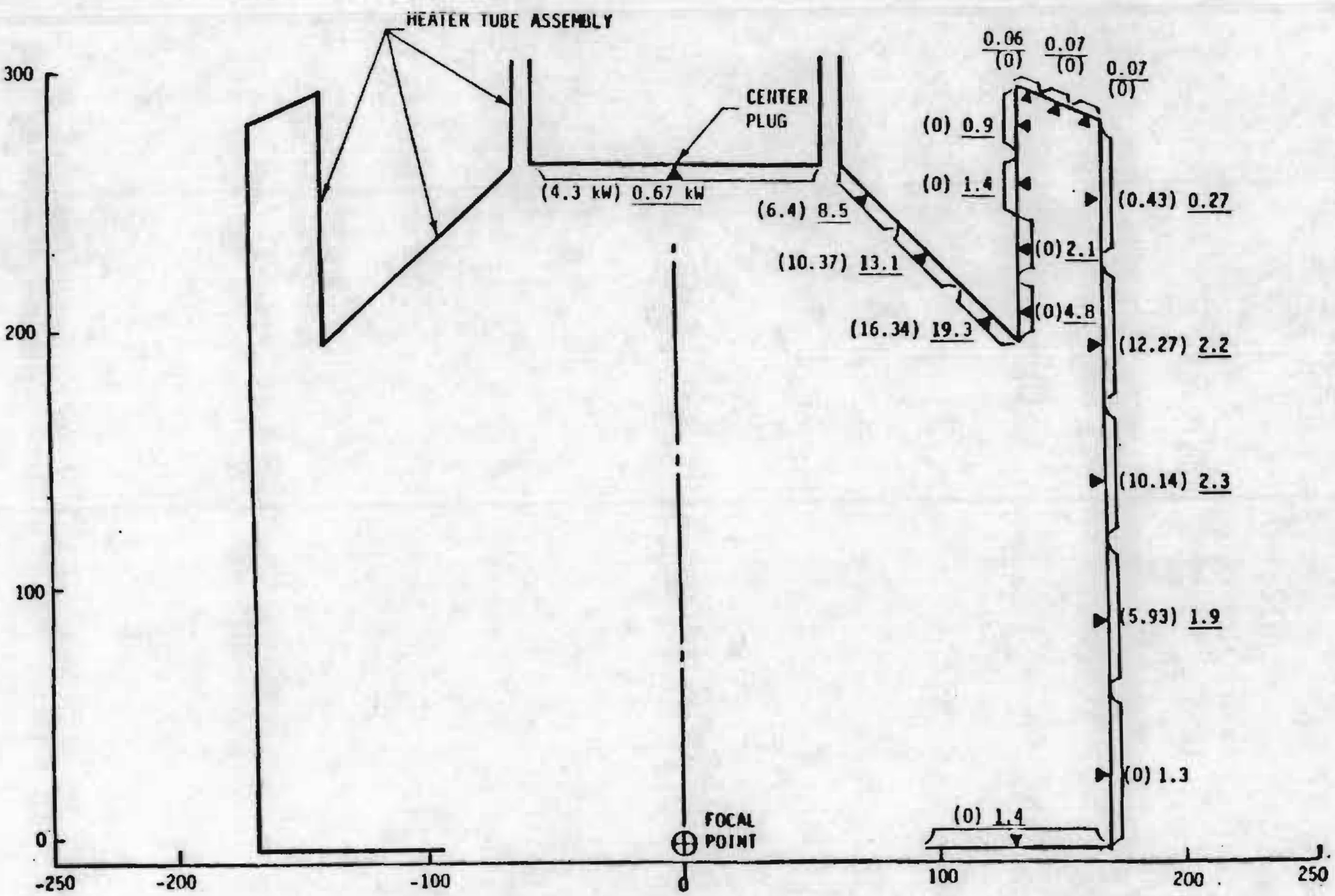

Figure 4. Cavity Configuration #4. Advanco Flux Pattern (X.XX) Incident Flux. <u>X.XX</u> Net Flux.

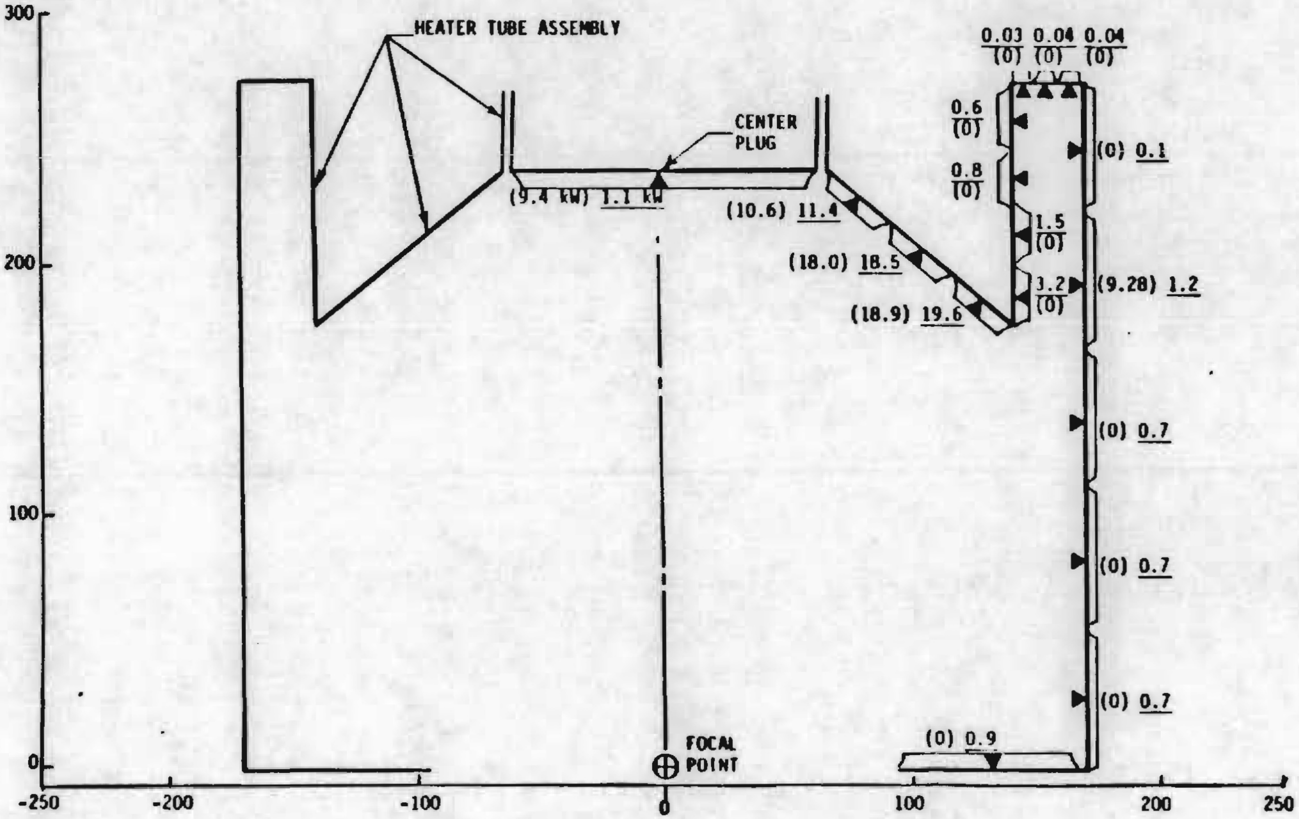

Figure 5. Cavity Configuration #5. Advanco Flux Pattern
(X.XX) Incident Flux. X.XX Net Flux.

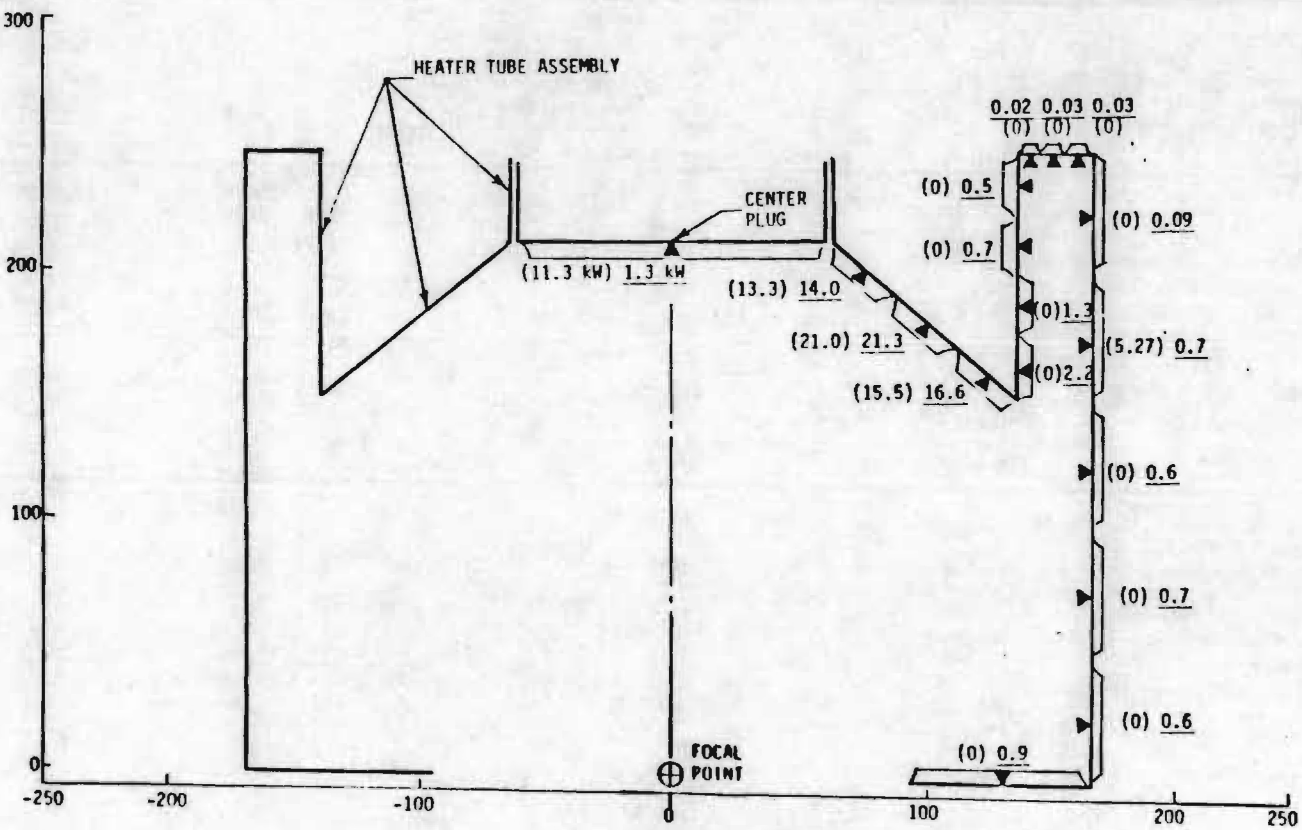

Figure 6. Cavity Configuration #6. Advanco Flux Pattern.
(X.XX) Incident Flux. X.XX Net Flux.

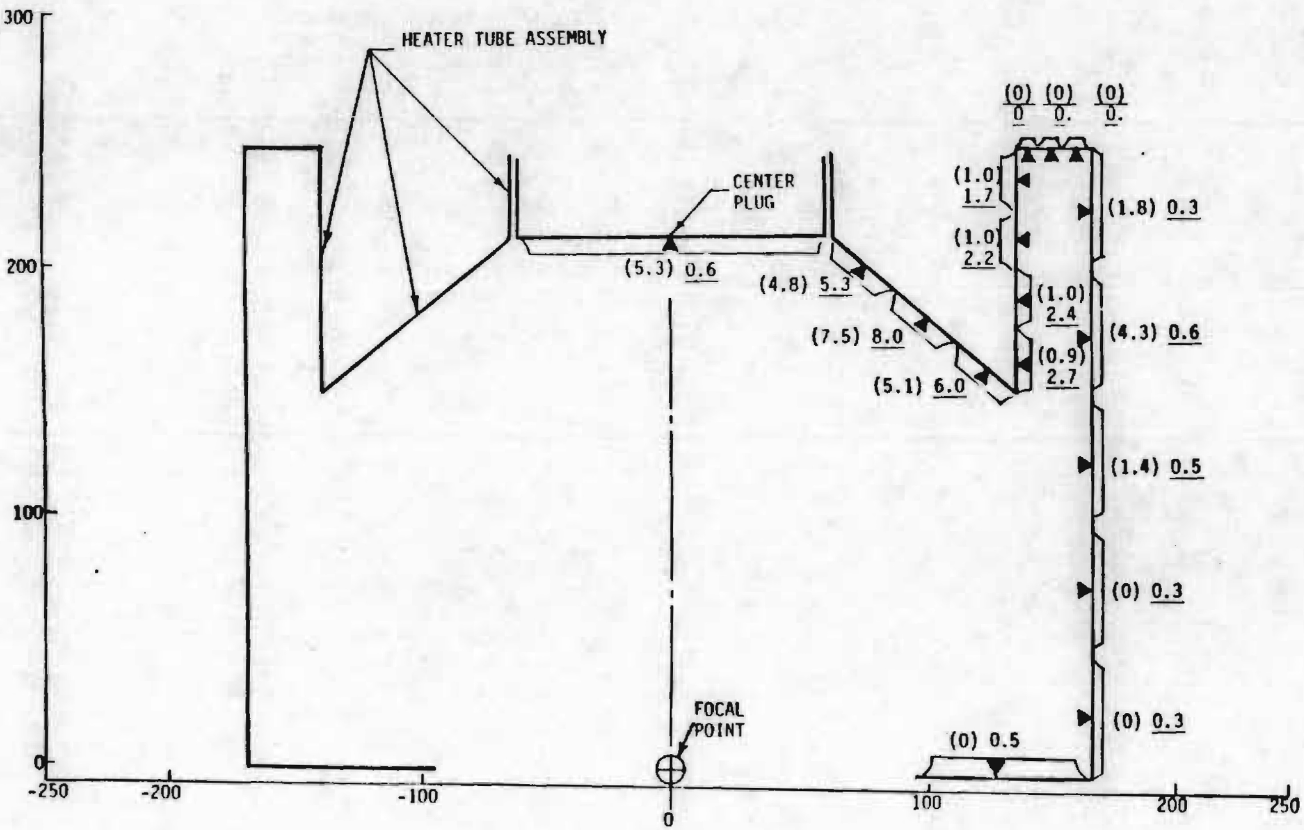

Figure 7. Cavity Configuration #6 ACTF Flux Pattern. Transparent Cone.
(X.XX) KW Incident Flux. X.XX KW Net Flux.

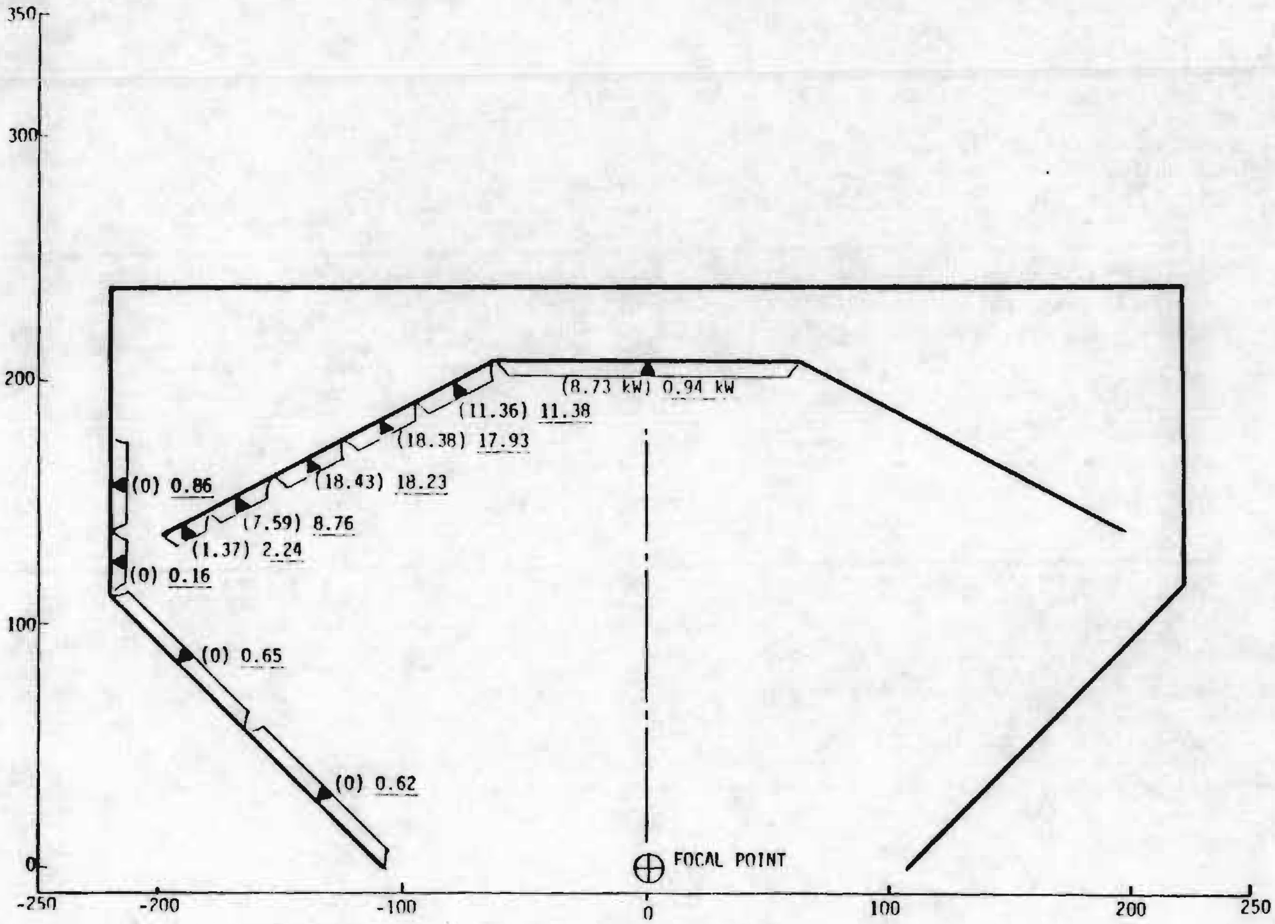

Figure 8. Extended Heater. Vertex of Heater Cone 240 mm from Focal Plane. Advanco Flux.

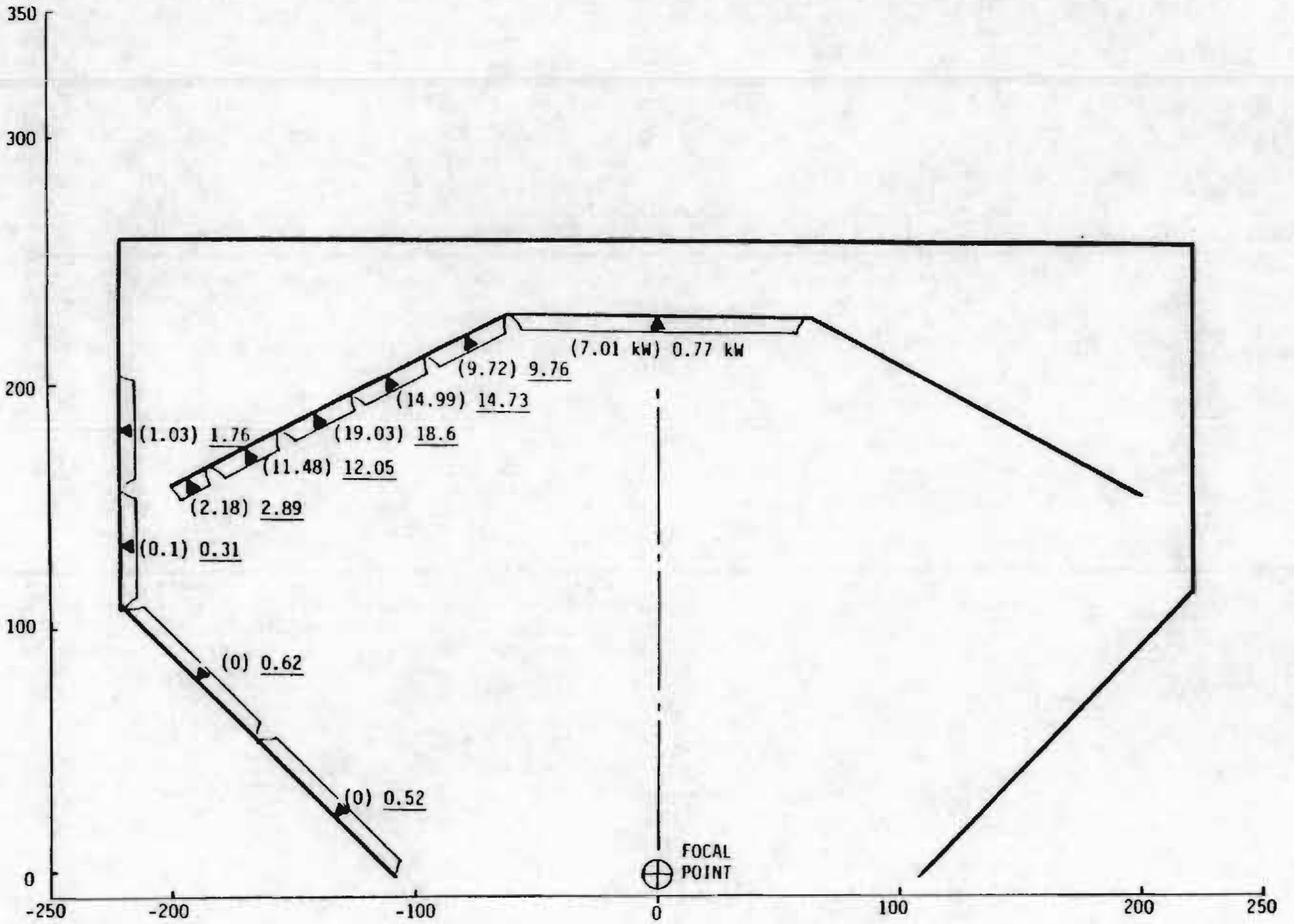

Figure 9. Extended Heater. Vertex of Heater Cone 260 mm from Focal Plane. Advanco Flux.

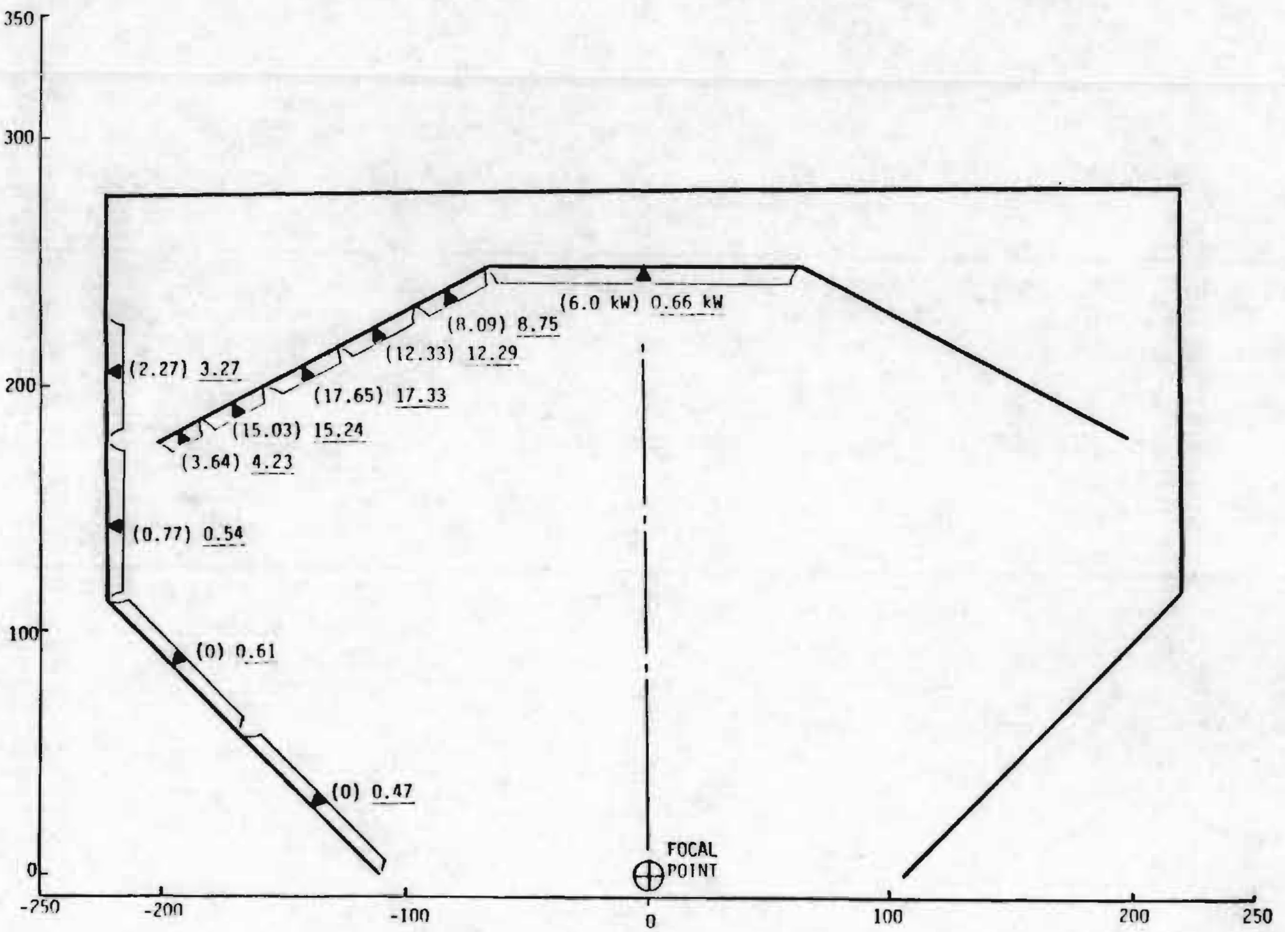

Figure 10. Extended Heater. Vertex of Heater Cone 280 mm from Focal Plane. Advanco Flux.

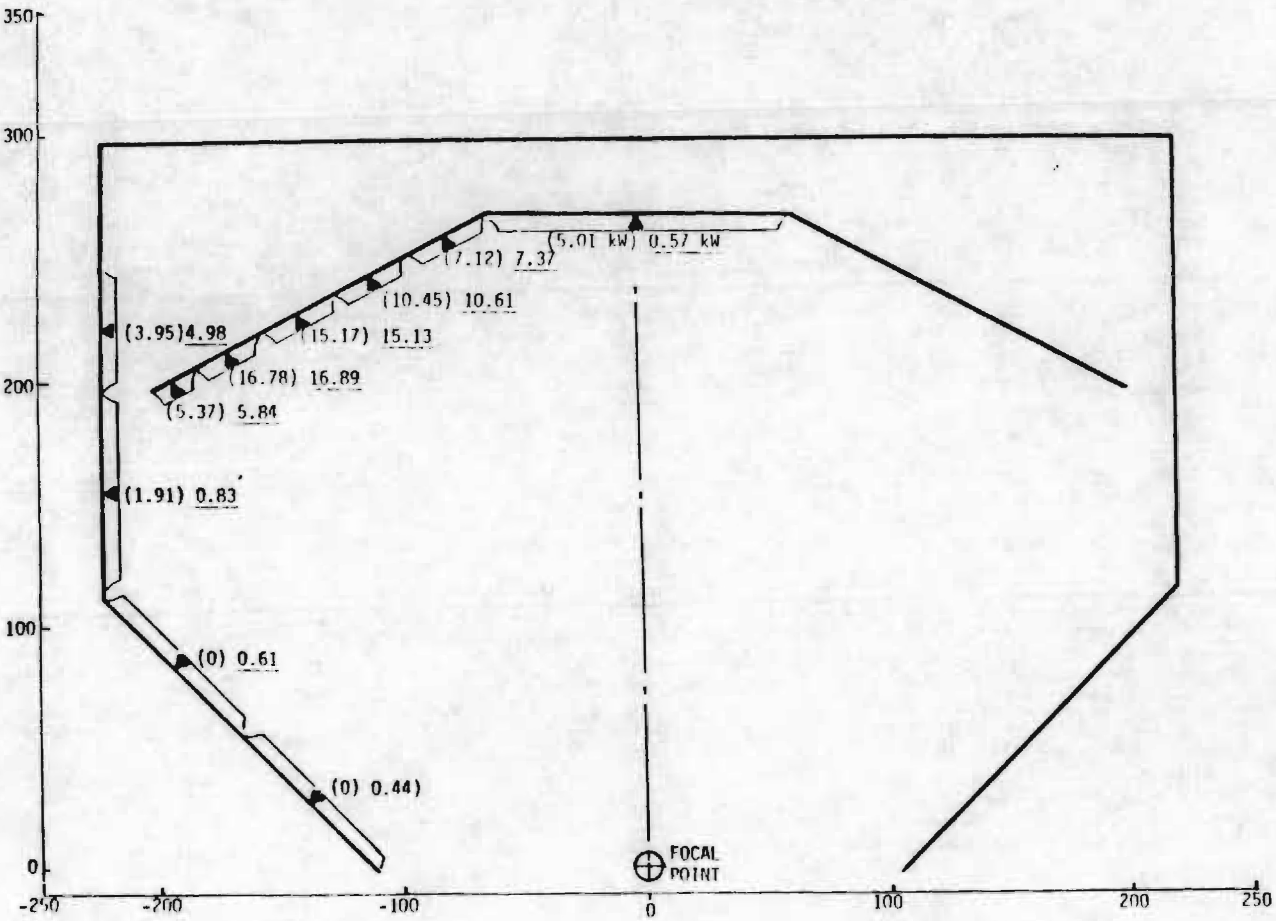

Figure 11. Extended Heater. Vertex of Heater Cone 300 mm from Focal Plane. Advanco Flux.

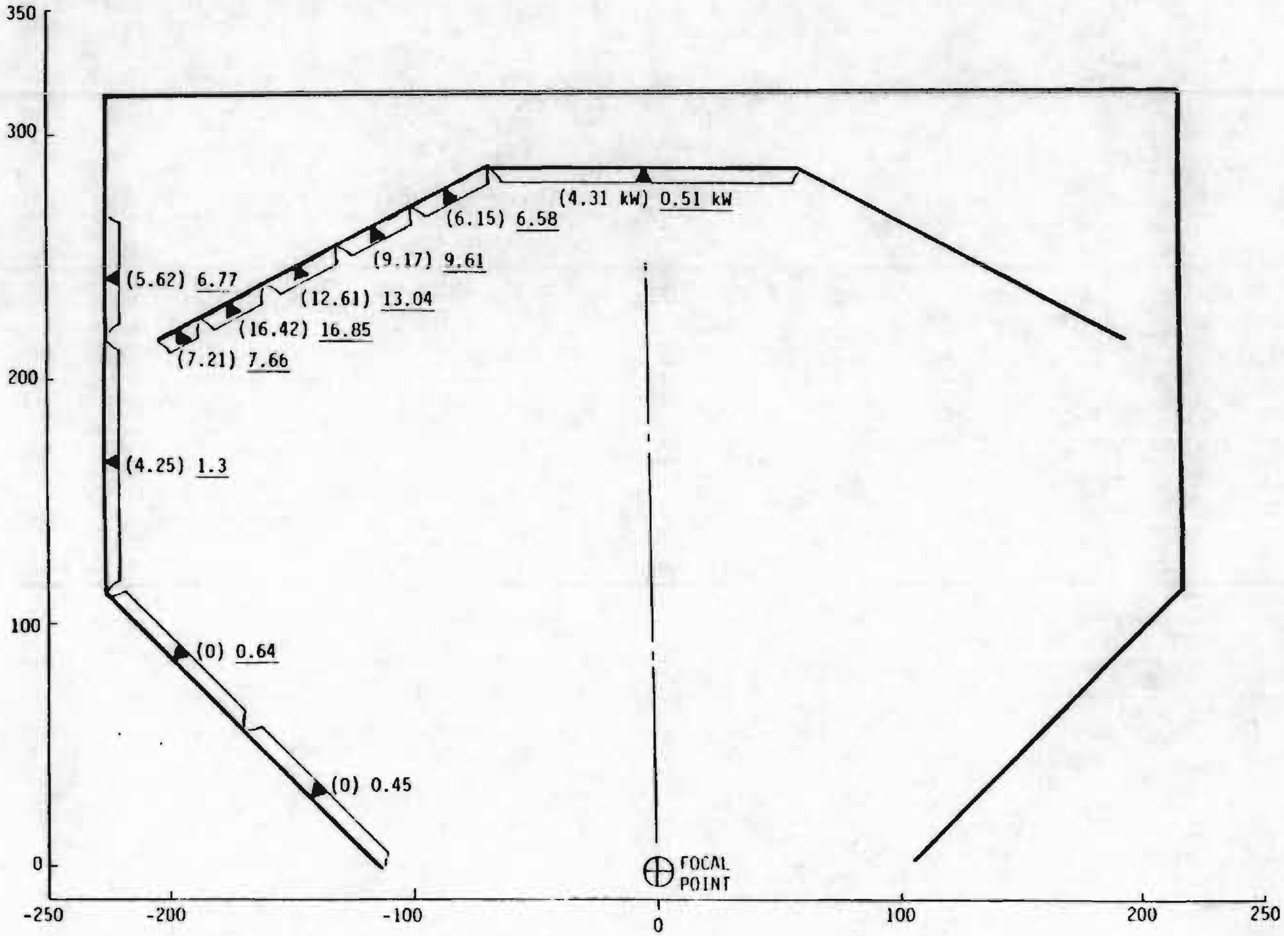

Figure 12. Extended Heater. Vertex of Heater Cone 320 mm from Focal Plane. Advanco Flux.

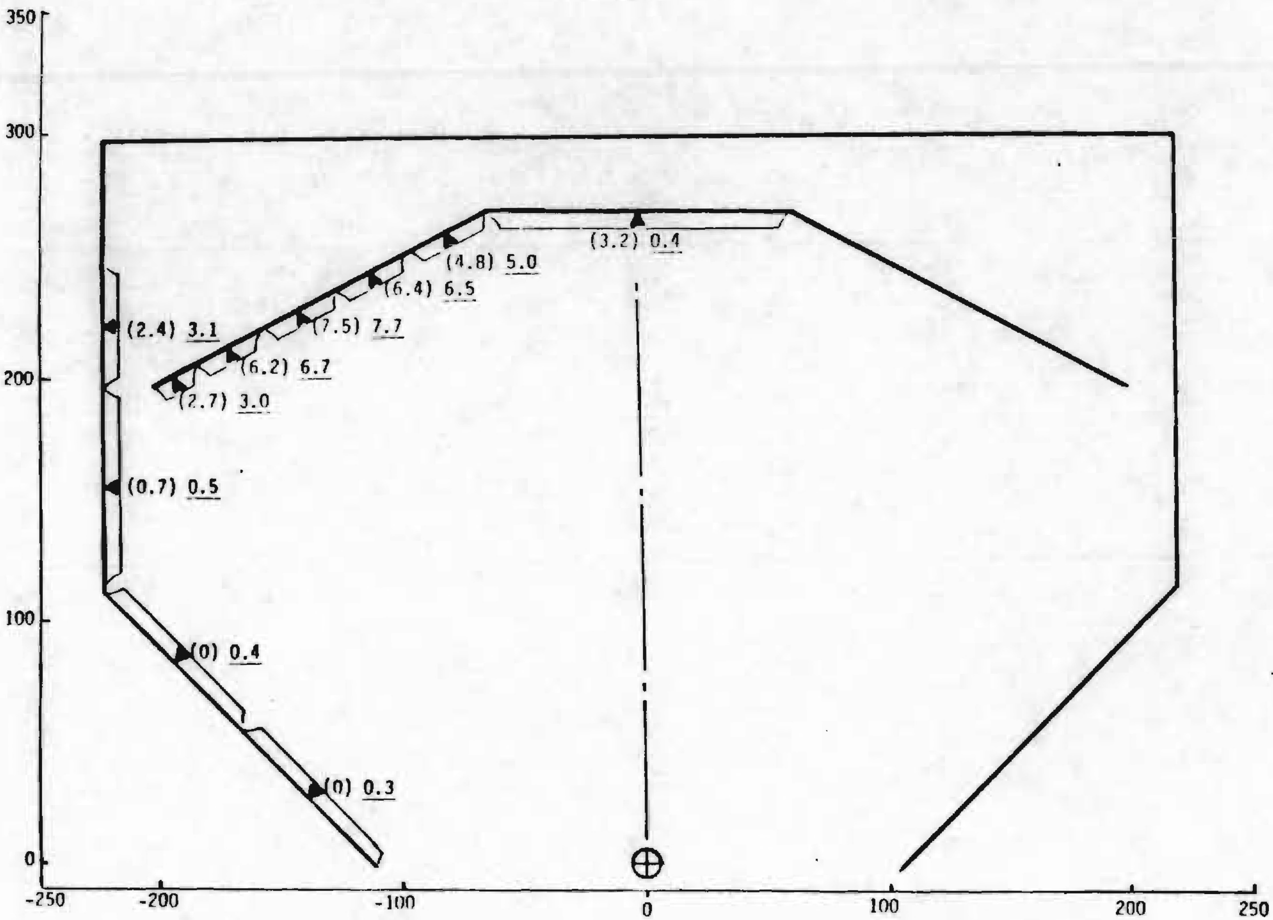

Figure 13. Extended Heater. Vertex of Heater Cone 300 mm from Focal Plane.
ACTF Flux. (X.XX) KW Incident Flux. X.XX KW Net Flux.

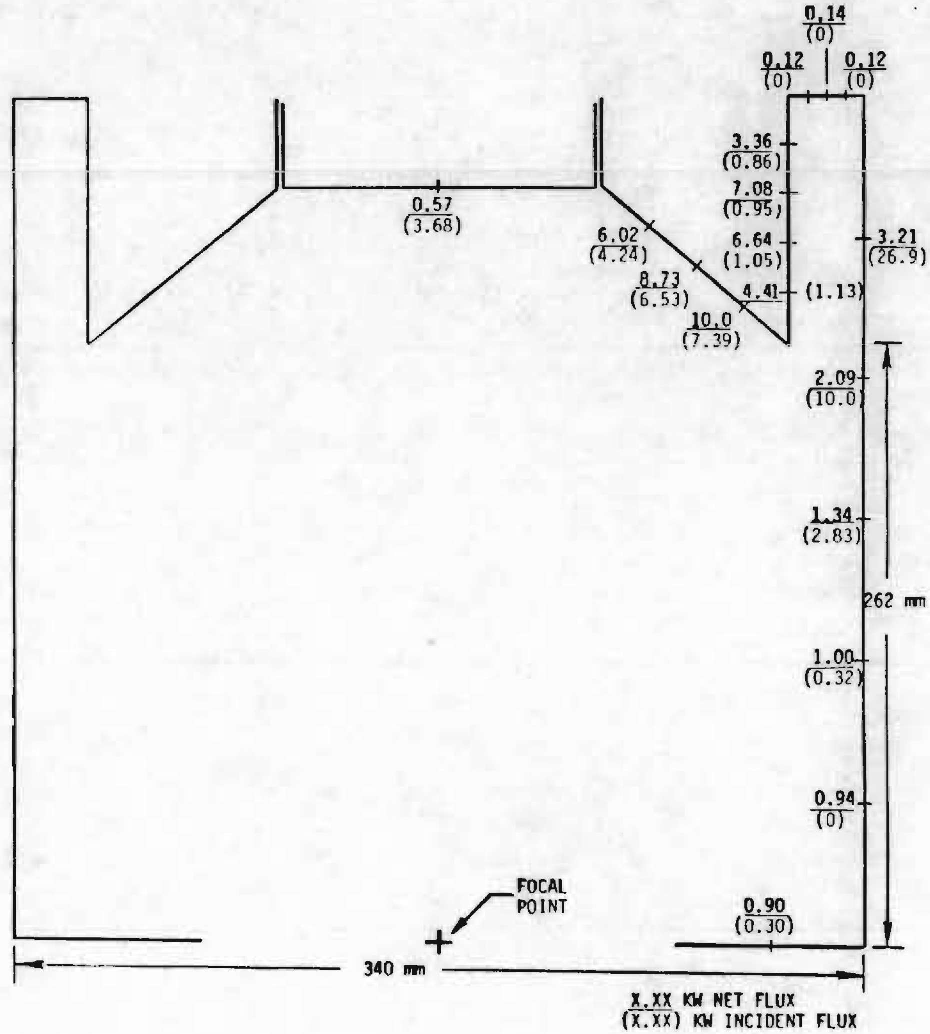

Figure 14. Advanco Flux Pattern. Deep Cavity. Transparent Cone.

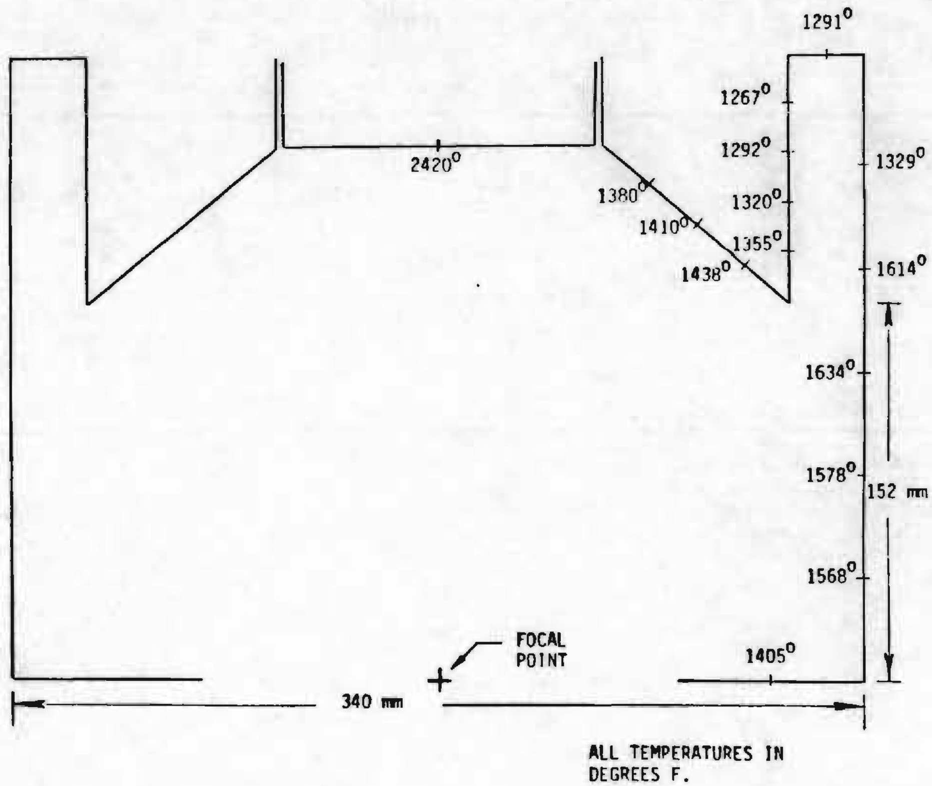

Figure 15. Cavity Temperatures for Optimum Cavity 1200° Helium. Advanco Flux Pattern. 183,600 Btu/hr into Helium.

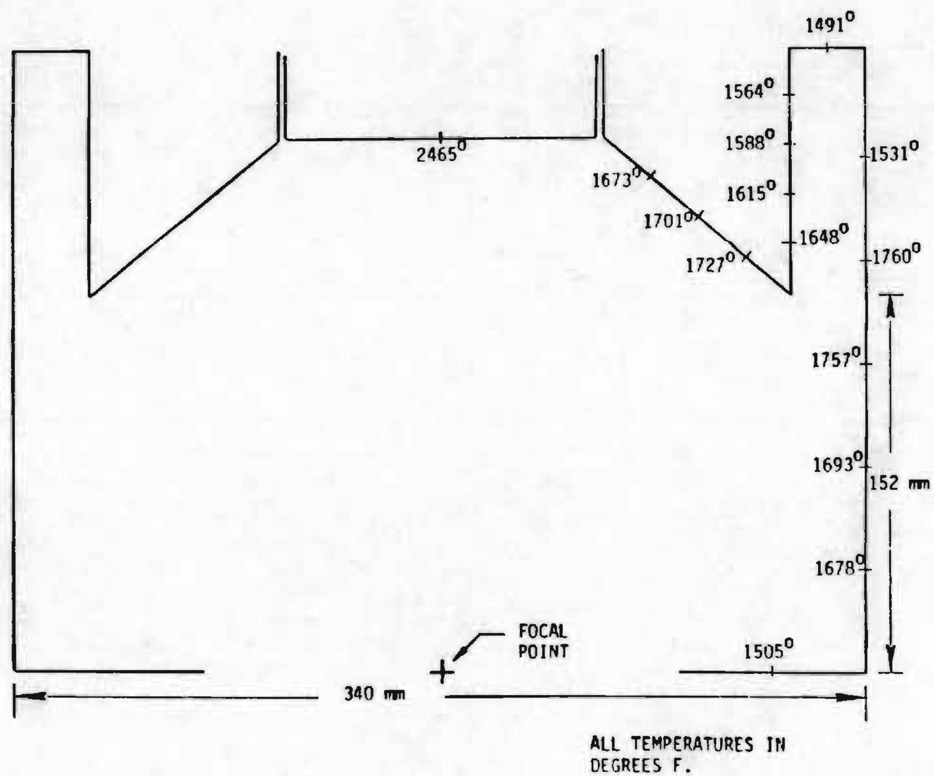

Figure 16. Cavity Temperatures for Optimum Cavity 1500° Helium. Advanco Flux Pattern. 178,776 Btu/hr into Helium.

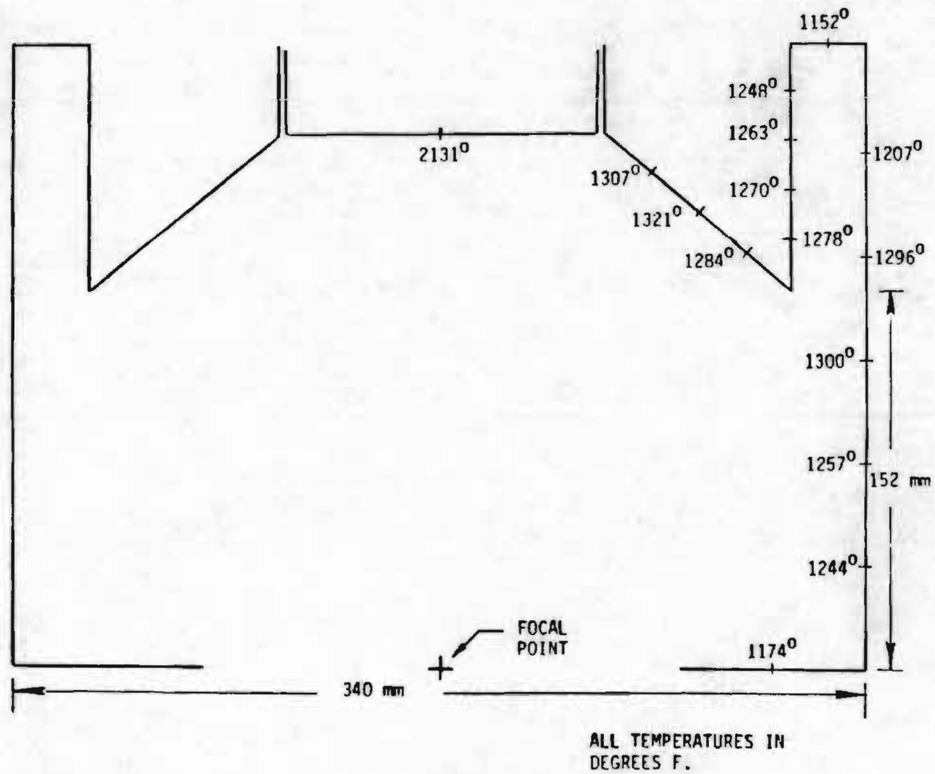

Figure 17. ACTF Flux Pattern; 1200^0 Helium; 94,248 Btu/hr into Helium.

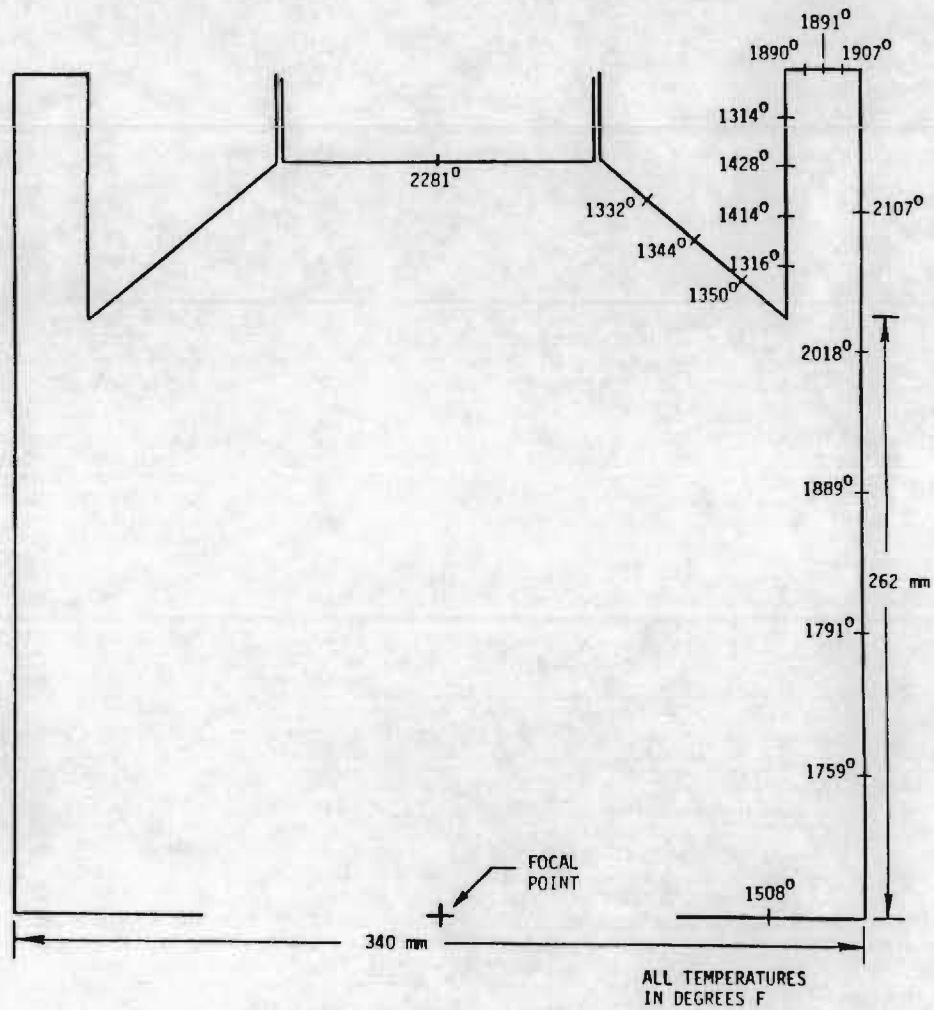

Figure 18. Advanco Flux Pattern; 1200^{o} Helium; 171,122 Btu/hr into Helium. Deep Cavity.

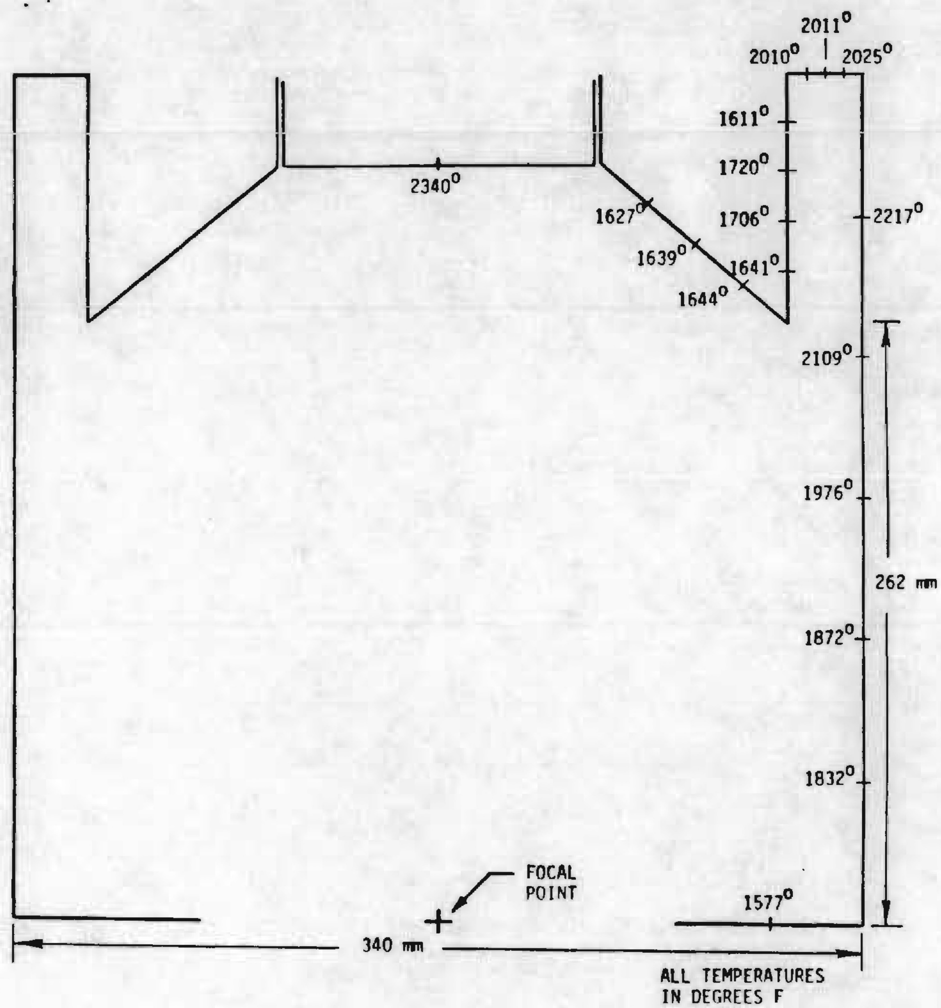

Figure 19. Advanco Flux Pattern; 1500° Helium; 168,028 Btu/hr into Helium. Deep Cavity.

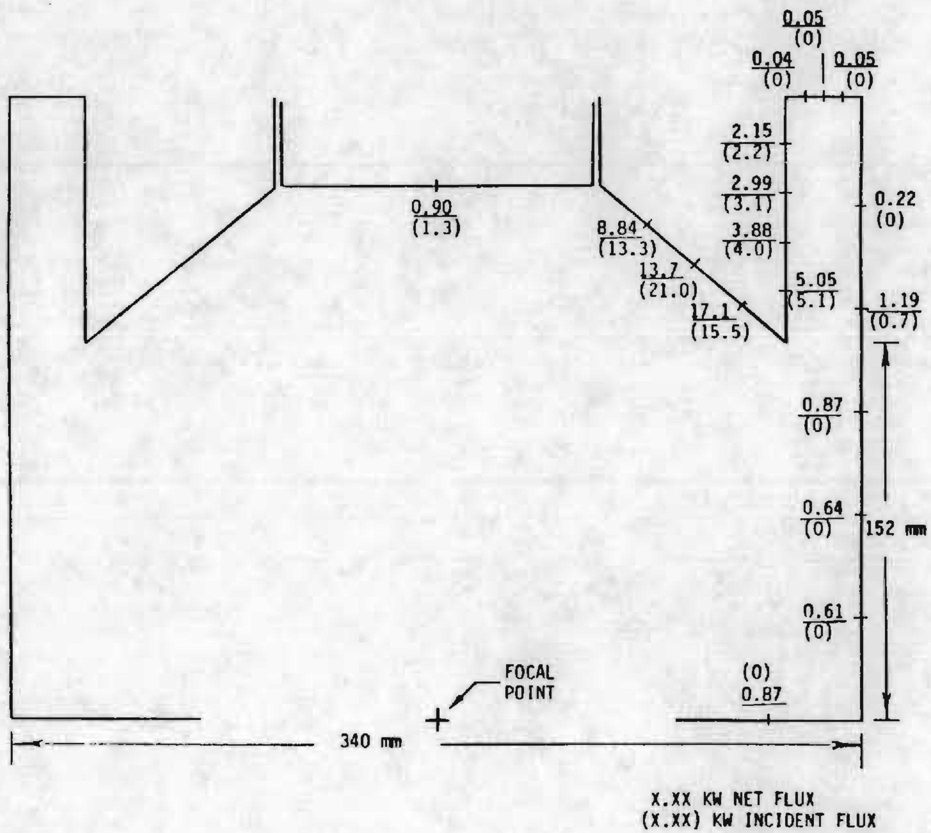

Figure 20. Advanco Flux Pattern. Transparent Heater.